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Mineral raw material requirements and associated climate-change impacts of the French energy transition by 2050

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ABSTRACT

In France, significant investments regarding renewable energy power plants will be required in future years in order to attain targets set by French and European regulations. This study aims *i)* at quantifying the requirements for steel, aluminium, copper (among the most impactful metal productions with respect to climate change in the world) and concrete resulting from the projected energy transition in France by 2050 (with a focus on the power sector) and *ii)* at estimating the climate change impacts associated with the production of these raw materials. As a basis to the modelling exercise, coefficients of material intensities of electricity generation systems were collected from the literature. Despite the variety of data sources, uncertainties regarding the information gathered on material intensity are of an epistemic nature, reflecting incompleteness. Therefore possibility theory was used to represent uncertainties relative to these parameters and to propagate uncertainty in the calculation. Results are expressed as upper and lower bounds on the probability that requirement for materials, and subsequent climate change impacts of their production, should be lower than a certain value. From these limiting bounds, values are derived for an 80% confidence index and put in perspective with current consumption of raw materials and greenhouse gas emissions of specific French economic activities. In particular, there is a 20% risk that requirements for steel be greater than 46,000 ktonnes (corresponding to 20 years of steel products consumption by the French automotive sector) and for aluminium be greater than 6360 ktonnes (21 years of aluminium consumption by the French building sector). Moreover, there is a 20% risk that the production of steel, copper, aluminium and concrete, as a response to the French energy transition, induces more than 445 million tonnes of CO_2-eq. The results provide decision-makers with a basis to decide whether the calculated risks of raw material consumption and corresponding climate change impacts are acceptable, taking into account other types of activities.

1. Introduction

In order to address the Kyoto protocol targets in terms of greenhouse gas emissions and environmental protection, and in the meantime to secure the European energy supply, the European Directive 2009/28/EC promotes the use of energy from renewable sources. Twenty percent of electricity generated from renewables is targeted by 2020 in the European Community, with specific values regarding each Member State. In France, the target is set at 23% by 2020, compared to 10.3% observed in 2005 (Journal officiel de l'Union européenne, 2009; CGDD, 2016). The French "Energy transition for green growth act", adopted in 2015, goes further by setting a 32% target for renewables in the French electricity production mix by 2030 (Légifrance, 2015).

French electricity, i.e. electricity produced in France (and that represents the largest proportion of electricity consumed in France), is mainly generated from nuclear energy (76.34% in 2015), whereas renewables represent a much lower contribution (17.42%; RTE, 2016). Renewable electricity is presently primarily hydroelectricity (10.75% of the total French electricity generation) while wind, bio- and solar electricity still represent relatively limited contributions (respectively 3.86%, 1.45% and 1.36% of the total). Therefore, although electricity produced from renewables has increased by 50% since 2005, relatively important investments in renewable power plants are still needed in order to reach the

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targets set by French and European regulations. Several prospective scenarios anticipating the deployment of the French energetic transition with the goals set in the policies were published by several different institutions (ANCRE, 2013; ADEME, 2014; Négawatt, 2018).

Infrastructures that provide renewable energies require the use of a wide variety of raw materials and in particular metals. For example, specifically considering wind, photovoltaic and hydraulic electricity generation systems, requirements cover most elements of the Mendeleiev periodic table; i.e., Rare Earth Elements (REE; e.g. dysprosium, neodymium, praseodymium), metalloids (germanium, selenium, tellurium, etc.), post-transition metals (aluminium, cadmium, copper, gold, etc.), and transition metals (chromium, iron, nickel, etc.) – in addition to other raw materials (concrete, steel, cement, epoxy, glass, oil, etc.; Öhrlund, 2011; Moss et al., 2013; Marscheider-Weidemann et al., 2016; Resnick Institute, 2011; Zimmermann et al., 2013; Hertwich et al., 2015; De Ridder, 2011; Flury and Frischknecht, 2012; Ribeiro and da Silva, 2010). Therefore in order to achieve the energy transition, these resources will need to be mobilized in a context where they are (and will be) simultaneously required by several economic sectors other than energy, and where their global demand will be on the rise (Krausmann et al., 2009; Vidal and Arndt, 2013; Hatayama et al., 2010; Glöser et al., 2013).

Several recent studies have aimed at quantifying the needs for mineral raw materials in relation with the energy transition, with various scopes in terms of traced metals and materials, electricity production systems, or geographical and temporal coverages (Öhrlund, 2011; Moss et al., 2013; Zimmermann et al., 2013; Vidal et al., 2013; Harmsen et al., 2013; WWF, 2014; Månberger and Stenqvist, 2018; Valero et al., 2018). This study has similar objectives but with a focus on the French electricity transition by 2050. The analysis considers requirements in steel, aluminium, copper and concrete, similarly to Vidal et al. (2013), as these four materials are the main raw material requirements for the construction of electricity generation systems and, as a consequence, there are data available in the literature regarding their relative intensities (in terms of mass per MW installed). Steel, aluminium, copper and more generally any other metal utilized in infrastructures in France are derived from metal ore extraction performed outside Metropolitan France. The latter therefore depends on other countries' metal production (from ore extraction to metallurgy) to supply its economy (Minéralinfo, 2014). Moreover, due to their relatively important yearly production volumes, global iron, aluminium and copper productions are among the most impactful metal productions with respect to climate change (Nuss and Eckelman, 2014).

In this context, this study offers three main differences and improvements compared to current literature on the issue: *i)* its geographical and temporal scopes: France by 2050; *ii)* it not only considers masses of materials but instead additionally quantifies climate change impacts in a consequential approach; and *iii)* it accounts for data incompleteness in the assessment. To present these improvements, the paper is organized as follows: the method chapter describes the methodology deployed in this study, based on an extended literature review of raw material requirements in the different electricity generation systems. Then the results and discussion chapter offers an interpretation of the different results obtained, including the climate change impacts of these raw materials requirements. The paper ends with concluding remarks and some avenues for future research. The paper therefore offers a first estimate of raw material requirements for the French energy transition that takes into account expert judgments and data incompleteness by applying possibility theory.

2. Method

2.1. Objective and assessment approach

The objective of this study is to quantify the need for one alloy (steel), two metals (aluminium and copper) and concrete, and the subsequent climate change impacts relative to their production, as a result of the energy transition in France by 2050. This study focuses on electricity generation systems implemented through the energy transition. Only the direct requirements for materials are considered, implying that upstream requirements for materials in the supply chain of electricity generation systems are excluded from this study. Moreover, aspects of the energy transition that are not related with electricity generation (e.g., the use of alternative materials for energy efficiency improvement in the building sector), and those related with electricity distribution and storage, are also disregarded.

The calculation approach distinguishes three steps. Firstly, the intensity in direct requirements for materials is established for several electricity generation systems (in tonnes of materials/MW installed). In a second step, the climate change impacts of steel, aluminium, copper and concrete productions are calculated in tonnes CO_2-eq/tonne of materials. In both cases (material intensity and climate change impacts), coefficients are set as fixed, meaning that this study disregards the potential future changes in material intensity of electricity generation systems, and in greenhouse gas emissions induced by the production of these materials. Finally, a prospective scenario of energy transition in France by 2050, detailing potential future capacities installed from 2012 to 2050, is drawn from the literature.

2.2. Material intensity of electricity generation systems

2.2.1. Literature review

Data on direct material (steel, aluminium, copper and concrete) intensity of electricity generation systems were compiled from a variety of literature sources distinguishing wind power (respectively on-shore and off-shore), photovoltaic (PV, respectively rooftop and ground-mounted), hydraulic, nuclear and natural gas. On the one hand, the literature reviewed and screened in the Life Cycle Harmonization Project of the National Renewable Energy Laboratory (NREL, 2016) was used as a basis for data compilation in this study, considering wind, PV, hydraulic and nuclear electricity generation systems (Table 1). Only the publications that passed NREL's screening were considered further in this step of data mining. The screening performed by NREL is based on three different criteria: the LCA method applied in the study has to follow ISO 14040 and 14044 rules and has to include the major contributors to the climate change impact; the reported data have to be transparent and complete and the technologies evaluated have to be relevant to the energetic transition deployment (Dolan and Heath, 2012). On the other hand, regarding hydraulic and natural gas electricity generation systems, a complementary literature review was performed in the absence of any similar harmonization study at the time this work was carried out. Likewise, in the specific case of ground-mounted PV systems, a complementary literature review was performed in order to reach an appropriate number of data points (Table 1).

Among the publications that passed NREL's screening, only some actually provide data of direct requirements for materials. Data have accordingly been drawn from 4 to 14 publications (respectively regarding off-shore and on-shore wind), resulting in 4–26 sets of coefficients of material intensity (in tonnes of steel, aluminium, copper and concrete per MW of installed capacity; Table 1). Finally, specifically considering PV and wind electricity

Table 1
Material intensity of electricity generation systems: synthesis of the approach adopted to perform the literature review.

Electricity generation system	Reference publication for the literature review	Number of publications finally used	Number of data points[a]	System boundaries
Rooftop PV	From the Life Cycle Harmonization Project: Hsu et al., 2012; Kim et al., 2012	6	14 related to panels, 13 related to Balance Of System	Panels + Balance Of System
Ground-mounted PV	From the Life Cycle Harmonization Project: Hsu et al., 2012; Kim et al., 2012 As a complementary source of data for Ground-mounted PV: Beylot et al., 2014	7 (but only 2 referring to Balance Of System)	7 related to panels, 5 related to Balance Of System	
Off-shore wind	Dolan and Heath, 2012	4	4	Wind turbine (tower, rotor and nacelle), foundations and connection to grid
On-shore wind	Dolan and Heath, 2012	14	26	
Hydraulic	Own literature review (see Supporting Information document)	5	6	Dam structure, powerhouse buildings, penstocks, generators and turbines
Natural gas	Own literature review (see Supporting Information document)	5	5	Pipelines + Power plant
Nuclear	Warner and Heath (2012)	6	8	Nuclear power plant

[a] Each set of four coefficients of material intensity (with respect to steel, aluminium, copper and concrete) is considered a "data point" in this column.

generation systems, the collected data have been harmonized, in order to account for common parameters and system boundaries in all studies from the literature (see Supporting Information document).

2.2.2. Possibility distributions

In all the cases of electricity generation systems, values of material intensities (e.g. as steel) drawn from the literature are dispersed among relatively large ranges. This partly results from the variability in the use of materials from one plant design scheme to the other, from one technology to the other, etc. Such variability could be adequately represented by use of statistical distributions if sufficient data were available in order to identify these distributions. Yet although this study offers a relatively large number of data points on material intensity of electricity generation systems, the data is nevertheless scarce and insufficient to derive consistent statistical distributions in the context of the French energy transition. It was therefore preferred in the following to select an approach that accounts for the inherently incomplete nature of available information regarding material intensity and to accordingly formalize this information using so-called possibility distributions (Zadeh, 1978; Dubois and Prade, 1988; Dubois et al., 1996).

It is recalled that a possibility distribution (or fuzzy number) takes the form of a fuzzy set membership function (noted μ) such that $\mu(x^*) = 1$ for some (or several) value(s) x^* of a parameter X. This function describes the degree of possibility that $X = x$. While the simplest possibility distribution is the familiar min-max interval (where possibility equals 1 for values x located within the interval and 0 for values outside the interval), an "expert" is often able to express preferences within such an interval. This leads to more elaborate possibility distributions; e.g. triangular or trapezoidal. The likelihood of an event A, for example, that the value of parameter X should lie within a certain interval *A*, is described by two indicators: the possibility measure (Π) and the necessity measure (N). The possibility measure of the event is defined as:

$$\Pi(A) = \mathrm{Sup}_{x \in A}\mu(x) \tag{1}$$

where Sup denotes the largest value. In probabilistic terms, a degree of possibility can be viewed as an upper probability bound (Dubois and Prade, 1992). The dual function of a possibility measure Π is the necessity measure (N), defined as:

$$N(A) = 1 - \Pi\left(A^C\right) \tag{2}$$

where A^c denotes the complement of A. Therefore a degree of necessity can be viewed as a lower probability bound.

When comparing a possibility distribution to a threshold (is imprecise parameter X lower than a certain value x?), the distribution can be seen as encoding a "family" of probability distributions, limited by an upper and a lower distribution:

$$\Pi(X \leq x) = \mu(x) \text{for } x \leq x^*, \text{and 1 otherwise(upper distribution)} \tag{3}$$

$$N(X \leq x) = 1 - \mu(x) \text{for } x \geq x^*, \text{and 0 otherwise(lower distribution)} \tag{4}$$

Possibility distributions have been found to be particularly well suited for the formalization of expert opinion (Dubois and Prade, 1988), because an expert tends to be consistent with him/herself: values of a parameter considered most likely are necessarily contained within the interval of values considered possible. In this study, possibility distributions were defined for each coefficient of material intensity using "best judgement" and based on the datasets collected from the literature. The definition of possibility distributions firstly requires setting the support, i.e. the interval of values considered possible (interval [a; d] in Table 2), and secondly the core, i.e. the interval of values considered most likely (interval [b; c]). Regarding coefficients of material intensity, the support has always been set so that it included all the values drawn from the literature. Said in other words, all the values of material intensities from the literature were considered possible. In many cases, the minimum and maximum literature values were set, respectively, as the lower and upper bounds of the support. But in some cases, i.e., when several literature values were seen to be "concentrated" close to the minimum or maximum of the data range, the support was extended beyond these extremes using an educated guess.

Moreover, the cores of the distributions were defined in two steps. The first step consisted in defining an interval of values in which literature data seemed visually most concentrated. In the second step, this interval was either reduced or extended as a function of data quality. In particular, data whose source publication was relatively old compared to other data, and/or that were not (or very little) detailed in the source publications, were excluded from the core (i.e. they were considered possible but less likely than core data). The method used for defining possibility distributions based on literature values is exemplified in the Supporting Information document for the case of steel and copper intensities of on-shore wind. The parameters (support and core) of the resulting 28 possibility distributions (four materials times seven

Table 2
Material intensity of electricity generation systems: parameter distributions, based on datasets drawn from the literature.

Material	Electricity generation system	Unit	Limits of the trapezoidal distributions[a]			
			a	b	c	d
Steel	Rooftop PV	tonne/MW	4	8	64	279
	Ground-mounted PV	tonne/MW	16	45	130	166
	Off-shore wind	tonne/MW	125	156	210	253
	On-shore wind	tonne/MW	54	105	160	204
	Hydraulic	tonne/MW	25	55	194	261
	Natural gas	tonne/MW	30	153	485	667
	Nuclear	tonne/MW	10	33	60	66
Aluminium	Rooftop PV	tonne/MW	6	13	60	97
	Ground-mounted PV	tonne/MW	10	31	60	133
	Off-shore wind	tonne/MW	0.3	0.7	3.1	5.3
	On-shore wind	tonne/MW	0.3	0.7	3.1	5.3
	Hydraulic	tonne/MW	0	0	0.1	0.1
	Natural gas	tonne/MW	0.0	0.2	0.3	0.3
	Nuclear	tonne/MW	0.0	0.1	0.2	0.2
Copper	Rooftop PV	tonne/MW	0	0	6	10
	Ground-mounted PV	tonne/MW	2	2	8	10
	Off-shore wind	tonne/MW	1.8	2.0	4.8	5.9
	On-shore wind	tonne/MW	1.4	1.8	3.7	6.1
	Hydraulic	tonne/MW	0.1	1.0	1.8	2.0
	Natural gas	tonne/MW	No data[b]	No data[b]	No data[b]	No data[b]
	Nuclear	tonne/MW	0.6	0.7	0.8	1.5
Concrete	Rooftop PV	tonne/MW	0	0	0	0
	Ground-mounted PV	tonne/MW	0	95	523	2827
	Off-shore wind	tonne/MW	1	576	1582	2588
	On-shore wind	tonne/MW	70	173	565	657
	Hydraulic	tonne/MW	552	5344	9825	15,727
	Natural gas	tonne/MW	20	48	98	108
	Nuclear	tonne/MW	20	175	460	560

[a] The interval [a,d] stands for the distribution support; [b,c] stands for the distribution core.
[b] In the absence of data, these values were set to 0 in the calculations.

electricity generation systems) are reported in Table 2.

2.3. Climate change impacts of materials production

This study additionally aims at quantifying the climate change impacts associated with the production of the four materials considered (steel, aluminium, copper and concrete) in relation to the energy transition in France by 2050, with a focus on the power sector. Therefore, a consequential approach (according to UNEP/SETAC definition; UNEP, 2011) was adopted to perform the cradle-to-gate assessment of these four materials, and subsequently infer their climate change impacts as a response to the French energy transition. The consequential cradle-to-gate inventories of materials production were drawn from ecoinvent v3.0 for use in this study. Moreover, for these life cycle inventories to be fully consistent with the approach developed by Weidema (2003), recent advances regarding the definition of marginal suppliers of copper concentrate, refined copper, aluminium and steel were considered as a complement (Table 3; Beylot, 2016a, 2016b; 2016c; by definition, the marginal suppliers are the ones that will change their production capacity in response to an accumulated change in demand). The climate change impacts of producing one tonne of copper, aluminium, steel and concrete were accordingly calculated by use of IPCC factors with a timeframe of 100 years (IPCC, 2013).

2.4. Scenario of energy transition

Future energy consumption and production, both at world and single country scales, have been subject to several prospective studies in recent years. In particular, the French National Alliance for the Coordination of Research for Energy (ANCRE) proposed three main scenarios of energy transition, which include *i*) reducing fourfold French emissions of greenhouse gases between 2012 and 2050, and *ii*) decreasing the proportion of nuclear energy in the electricity mix down to 50% in 2025 (ANCRE, 2013). The ANCRE scenarios have been chosen to conduct this study for two reasons: firstly, these scenarios have been obtained as a result of a collaboration between several research centers key in the development of the energy transition in France and, secondly, they report the figures on the cumulative investments in electricity generation systems from 2012 to 2050 (which are required to perform calculations in this study). The following only focuses on one of the ANCRE three main scenarios; i.e. the so-called « Decarbonization via electricity » scenario. It is characterized by a significant increase in electricity consumption, particularly in the transport sector (with 45% of electric mobility in 2050). Decarbonization is expected

Table 3
Cradle-to-gate climate change impacts of producing copper, aluminium, steel and concrete, in a consequential approach.

Material	Marginal supplier	Climate change impact (in kg CO_2-eq/ kg)
Copper	Chile: copper concentrate China: refined copper	3.99
Aluminium	China (both regarding alumina and primary aluminium)	25.7
Steel	China	2.84
Concrete	France	0.649

to be achieved thanks to improvements in energy efficiency, and to the increase in the use of electricity (from renewable and nuclear energy sources) that would substitute for fossil fuels. This is the ANCRE scenario requiring the largest investment in terms of new capacities of electricity production (Table 4) and hence tends to maximize future requirements for materials as a consequence of the French energy transition.

3. Results and discussion

3.1. Requirement for materials and corresponding climate change impacts by 2050

Results of the uncertainty propagation are expressed as limiting cumulative probability distributions for the proposals "requirement for materials (steel, aluminium, copper and concrete) is lower than a certain value" (Fig. 1) and "climate change impact is lower than a certain value" (Fig. 2). These limiting distributions are the possibility distribution (the upper bound on probability) and the necessity distribution (the lower bound on probability). Therefore the possibility distribution depicts the most "optimistic" probability distribution, as it provides the highest value of probability that material requirement (respectively climate change impact) should be lower than a certain value. Conversely the necessity distribution depicts the most "pessimistic" distribution. The distance between these two bounds is a direct consequence of the incomplete nature of the information available on material intensity of electricity generation systems.

Table 4
Main cumulative investments in electricity generation systems from 2012 to 2050, in the ANCRE scenario "Decarbonization via electricity" (ANCRE, 2013).

Electricity generation systems	Cumulative investments, 2012–2050 (GW)
Rooftop PV	39
Ground-mounted PV	39
Off-shore wind	39
On-shore wind	75
Hydraulic	4
Natural gas	25
Nuclear	45
Total investments	266

The requirement for steel as a response to the energy transition from 2012 to 2050 in France (with focus at the electricity sector) is estimated to lie between 11,300 ktonnes (10^3 tonnes) and 62,760 ktonnes at a probability level $\geq$ 95%, with [21,535; 43,390 ktonnes] as most likely values. Similarly, the requirement for aluminium lies between 690 ktonnes and 9550 ktonnes ($\geq$95% probability) and most likely between 1815 and 5115 ktonnes; that for copper between 285 ktonnes and 1540 ktonnes ($\geq$95% probability) and most likely between 360 and 1085 ktonnes; and finally that for concrete between 9580 and 339,275 ktonnes ($\geq$95% probability) and most likely between 66,300 and 180,840 ktonnes. Moreover, the cradle-to-gate climate change impacts relative to the production of these four materials, required as a response to the energy transition, are assessed to amount between 57 and 650 million tonnes of CO_2-eq ($\geq$95% probability), and most likely between 150 and 375 million tonnes of CO_2-eq (Fig. 2).

3.2. Confidence index on results

In a decision-making framework, it is not convenient to work with imprecise risk indicators. In fact, in the Bayesian tradition, one of the justifications for using subjective probabilities for input parameters is that a single probability estimator is required in order to

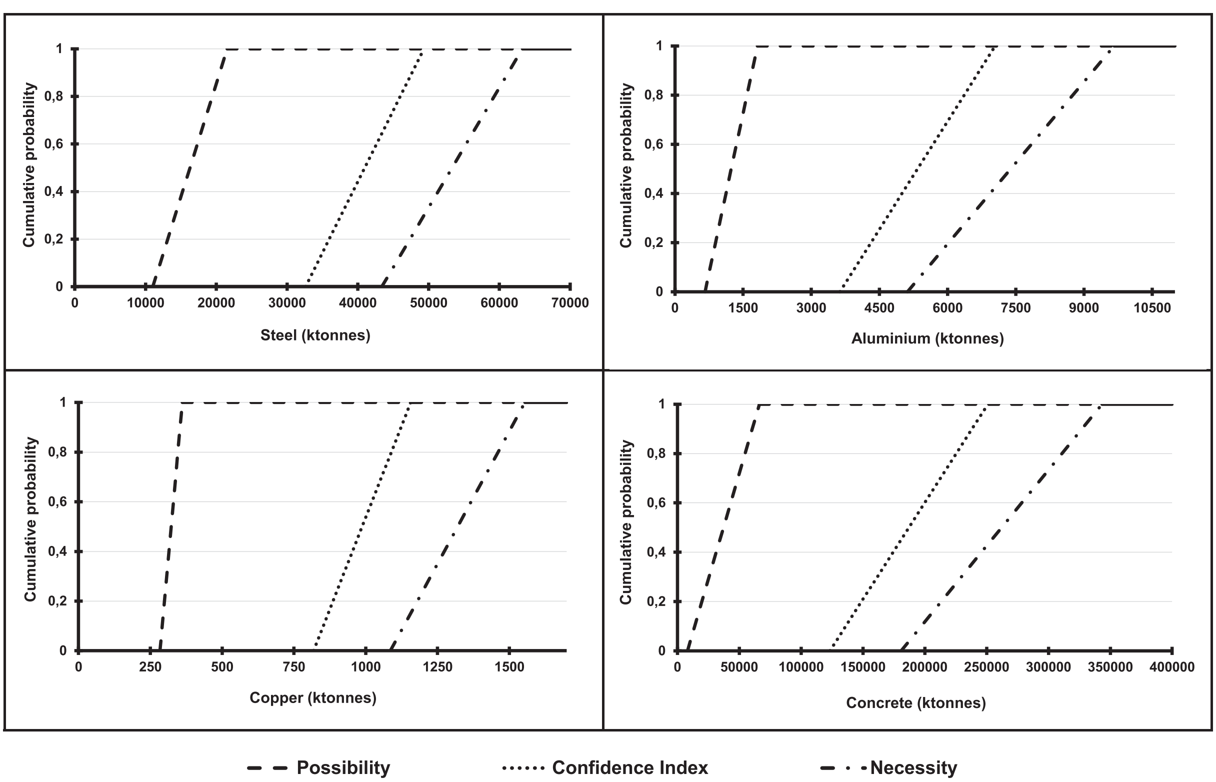

Fig. 1. Results of uncertainty propagation, as cumulative probability distributions for the proposal: "material requirement for the energy transition (as electricity only) is lower than a certain value" (in ktonnes).

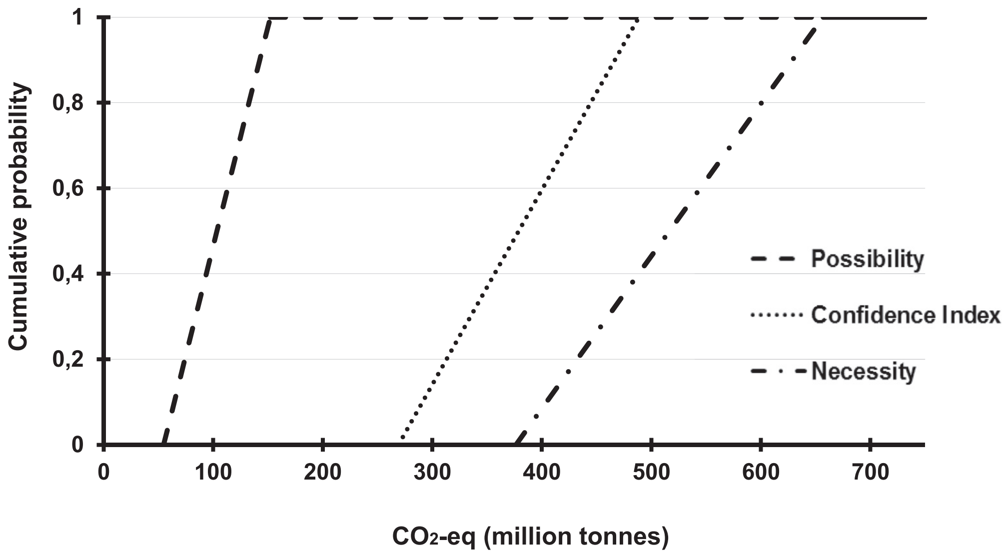

Fig. 2. Results of uncertainty propagation, as cumulative probability distributions for the proposal: "climate change impact of materials required for the energy transition (as electricity only) is lower than a certain value" (in million tonnes CO_2-eq).

ensure a rational decision. For this reason Dubois and Guyonnet (2011) proposed, based on earlier work by Hurwicz (1951), to compute a single indicator (dubbed "confidence index") as a weighted average of upper and lower bounds, thus allowing a trade-off between optimistic and pessimistic estimates. The confidence index is expressed as:

$$f(a_i, b_i) = \alpha a_i + (1 - \alpha) b_i \tag{5}$$

where a_i and b_i are, respectively, the Inf and Sup values of material requirement (and, respectively, climate change impacts) at probability level i, while α is a weighting factor. This procedure allows the decision-maker's "aversion to risk" to be taken into account. In a context of total aversion to risk, a value $\alpha = 0$ would be used, thereby giving no weight to the "optimistic" (upper) distribution in Figs. 1 and 2, while in a situation of no aversion to risk, a value $\alpha = 1$ could be used, thus considering only the "pessimistic" (lower) distribution. In practical situations, it would seem reasonable to give more weight to the pessimistic bound but without completely neglecting the optimistic one. If a weight of 1/3 is assigned to the optimistic bound and 2/3 to the pessimistic one, the distributions in Figs. 1 and 2 are obtained. The weighting factor in Eq. (5) is of course subjective, as it is selected to reflect the decision-maker's degree of aversion to risk. But this subjectivity is introduced at the final decision-making stage, which is more easily justified than to arbitrarily select single probability distributions at the modelling stage, despite incomplete information.

According to Fig. 1, the requirement for steel as a response to the French energy transition, from 2012 to 2050, is lower than 46,000 ktonnes with a confidence index value of 80%. Taking this confidence index as the sole indicator of likelihood, this is analogous to saying there is a 20% risk that requirement for steel be greater than 46,000 ktonnes. As a matter of comparison, one may note that 46,000 ktonnes approximately correspond to 20 years of steel products consumption by the French automotive sector (with year 2010 as a basis, and assuming that the shares of steel consumption by economic activities in Europe also apply to France; FFA, 2010; Minéralinfo, 2015). Similarly, there is a 20% risk that the requirement for aluminium as a response to the French energy transition be greater than 6360 ktonnes. The latter quantity corresponds to 21 years of aluminium consumption by the French building sector, which ranks as the second French economic activity with respect to aluminium consumption (considering year 2014 as a basis; Aluminium.fr, 2015). Finally, there is a 20% risk that the production of steel, copper, aluminium and concrete, as a response to the French energy transition, induce more than 445 million tonnes of CO_2-eq. The corresponding greenhouse gases, mainly emitted outside France, would correspond to 8 years of climate change impacts by the French energy sector (considering year 2011 as the reference; INSEE, 2012).

3.3. Analysis by electricity generation system and material

Photovoltaic (ground-mounted and rooftop) and wind (offshore and on-shore) electricity generation systems are predominant in the analyzed "Decarbonization via electricity" scenario, representing 72% of the cumulative investments from 2012 to 2050. As a result, these four electricity generation systems contribute to 68 (case of steel) and up to 100% (case of aluminium) of the requirement for materials induced by the energy transition, when considering results with a confidence index value of 80% (Fig. 3). In the scenario, on-shore wind is considered to be subject to the largest investments (28% of the total) and is therefore also the major source of requirements for both steel and copper (respectively 26 and 30% of their total requirement). Moreover, ground-mounted PV comes third in terms of investments (15%), but first regarding the induced requirement for aluminium (54%): this gap is due to the relatively large intensity in aluminium of ground-mounted PV systems compared to other electricity generation systems (Table 2). Ground-mounted PV is also the second source of requirements for both copper and concrete (respectively 26 and 28% of the total requirement), here again (but to a lower extent) due to its relatively large intensity in copper and concrete compared to other electricity generation systems.

Still considering results with a confidence index value of 80%, it can be noticed that the two electricity generation systems that have the largest contribution to climate change impacts are ground-mounted PV (32% of the total climate change impacts) and rooftop PV (19%; Fig. 3). This ranking is in relation with the total requirement for aluminium, for which ground-mounted and rooftop PV induce the largest contributions (94% in total). The total requirement for aluminium as a response to the energy transition is

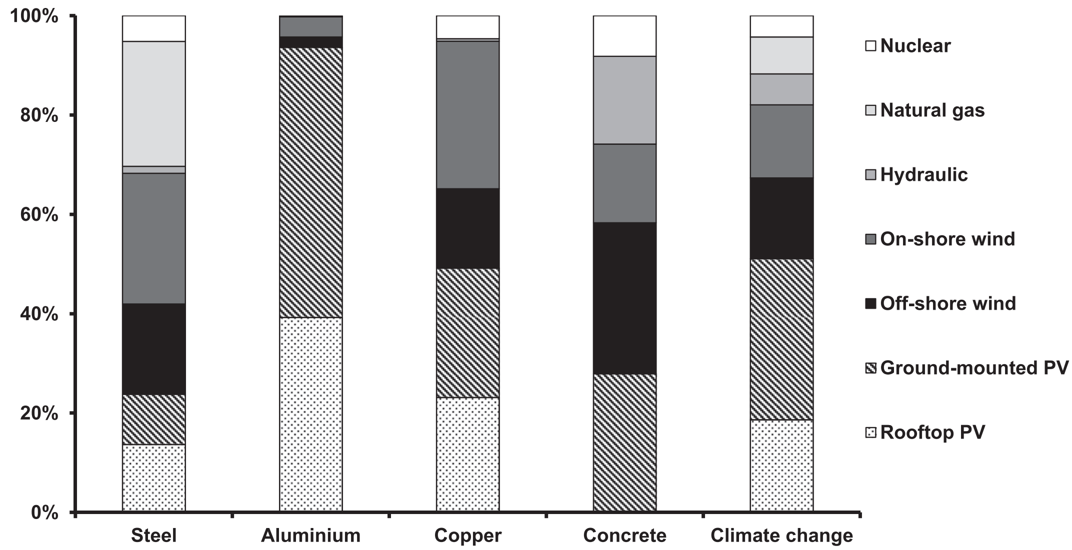

Fig. 3. Contribution of electricity generation systems to requirements for materials and climate change impact as a response to the energy transition from 2012 to 2050 in France, for a confidence index value of 80%.

7 times lower than that for steel, and 35 times lower than that for concrete. Yet, cradle to gate climate change impacts of aluminium production are respectively 6.4 and 40 times larger than those of steel and concrete productions (Table 3). As a result, total contributions of aluminium, steel and concrete productions as a response to the energy transition are relatively similar, ranging from 29 to 37%.

4. Conclusion and further research

In this study, the direct requirements for steel, aluminium, copper and concrete as a response to the French energy transition (with a focus on the power sector), and their subsequent climate change impacts, were quantified while taking into account uncertainties using a possibilistic approach. At the basis of the model, coefficients of material intensity of electricity generation systems were collected from a literature review. Despite the variety of data sources, the compiled information on material intensity was nevertheless very partial. Accordingly, instead of arbitrarily selecting probability distributions for representing uncertainty, as sometimes performed in the LCA of products and systems in such circumstances, coefficients of material intensity were represented by use of possibility distributions. This enabled to propagate epistemic uncertainties in the calculation of results.

Results were expressed as upper and lower bounds on the probability that requirement for materials, and the subsequent climate change impacts of their production, should be lower than a certain value. From these extreme bounds, a confidence index value of 80% was derived and values were put in perspective with current consumption of raw materials and greenhouse gas emissions of specific French economic activities. In particular, there is a 20% risk that requirements for steel be greater than 46,000 ktonnes (corresponding to 20 years of steel products consumption by the French automotive sector) and for aluminium be greater than 6360 ktonnes (21 years of aluminium consumption by the French building sector). Moreover, there is a 20% risk that the production of steel, copper, aluminium and concrete, as a response to the French energy transition, induce more than 445 million tonnes of CO_2-eq. Such results provide decision-makers with a basis to decide whether the calculated risks of raw material consumption and corresponding climate change impacts are acceptable, taking into account other types of activities. If they are not, options to divert the energy transition towards lower requirements for materials, with lower climate change impacts, should be considered. For example, in case the risk calculated with respect to the requirement for steel as a response to the energy transition is considered too high, PV systems equipped with wood structures might be an alternative to be favored in view of the relatively large contribution of ground-mounted PV systems to steel demand. More generally, policies aiming at the material efficiency of electricity generation systems (in a broad sense, encompassing ecodesign and improved energetic efficiency) should focus on systems deemed problematic in the above procedure.

Finally, it should be noted that the deliberate choice to limit this study to certain aspects of the French energy transition offers major perspectives for future improvement when developing a systemic vision of mineral resources needed for renewable energy development (as for example tackled by the SURFER project; ADEME, 2016). Of particular importance, this study focused on four materials only, including three metals (or alloy in the case of steel) that are required in relatively large quantities in electricity generation systems (compared to other metallic elements). Yet, electricity generation systems require a much larger range of materials, including many other metallic elements such as rare earths or gold, which generate much larger environmental impacts, on a per kg basis, than the considered metals (Nuss and Eckelman, 2014). Taking into account a larger set of metals would provide decision-makers with more complete information regarding the possible consequences of the energy transition in terms of material requirements and climate change impacts. It is anticipated that future requirements for, e.g., neodymium or dysprosium, would represent a far larger portion of current total consumption, considering the importance of these rare earth elements for permanent magnets used in particular in certain wind electricity systems. Moreover, in the calculations herein, material intensities and impacts were both considered constant from 2012 to 2050. A second major area for improvement would be therefore to implement a dynamic modelling approach. Such an approach would enable to account for potential future improvements in the material intensity of electricity generation systems, thanks to ecodesign strategies, or conversely, to account for potentially increasing climate change impacts of metal production in a context of decreasing mined ore

grades (Mudd, 2009).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2018.10.154.

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